DEPARTMENT OF COMMERCE
SINCLAIR WEEKS, Secretary

WEATHER BUREAU
F. W. REICHELDERFER, Chief

MONTHLY WEATHER REVIEW

JAMES E. CASKEY, JR., Editor

Volume 84
Number 8

AUGUST 1956

Closed October 15, 1956
Issued November 15, 1956

AN ANALYSIS OF A CYCLONE ON A SMALL SYNOPTIC SCALE[1]

JEROME SPAR

New York University, New York, N. Y.

[Manuscript received August 6, 1956]

ABSTRACT

A fast-moving, rapidly-deepening cyclone is analyzed mainly by means of hourly airways sequence reports in the Atlantic coastal plain of the United States.

Six-hourly rainfall maps are presented showing the concentration of heavy rain along the cyclone path, and the strongly convective character of the cyclonic precipitation.

Gusty surface winds are found mainly in the warm sector during the early stages of the cyclone. The momentum of the surface gusts is derived from that of higher layers and comes down to the surface in bursts through the unstable warm air. Because the stability of the frontal zone prevents the downward transport of gust momentum, the surface winds in the cold air are much lighter than in the warm air. However, in places the front is penetrated by the gusts, and the resulting vertical mixing brings warm air to the surface causing an acceleration of the surface warm front. As the cyclone deepens, the gust velocities increase in the cold air in proportion to the increase of pressure gradient. The momentum of the low-level jet at the top of the friction layer penetrates to the surface most readily when the surface pressure gradient force does not oppose the direction of the jet.

An analysis of hourly pressure changes shows the existence of large-amplitude, high-speed pressure pulses moving across the cyclone. The pulses result in deformation of the pressure field, the generation of secondary centers, and erratic motion of the cyclone.

1. INTRODUCTION

The scale on which weather analysis is carried out determines to a large extent the nature of the phenomena that are found. Every scale has its own characteristic phenomena which other scales of analysis may not reveal. Indeed much controversy in meteorology has resulted from the comparison of analyses on different scales; for analysts, examining the same system but under different degrees of magnification, may see quite different structures and processes.

The surface synoptic scale (corresponding to the separation of surface weather stations), to which synoptic meteorologists have become accustomed during the past 100 years, reached its zenith of productivity in the work of the Norwegian school about 1920. Since that time, and especially in the last 15 years, meteorological analysis has been extended over a broad spectrum of scales, but with some tendency for a concentration of research effort on a large scale corresponding to the hemispheric radiosonde network, and on a small scale corresponding to radar studies of rainstorm morphology and various dense networks of raingages and microbarographs. (The microscales used in some micrometeorological and turbulence studies are, of course, still smaller.)

There is a rough correspondence of the time scale to the space scale of the analyses that is dictated by the cost of the observations and the velocities of disturbances.

Weather forecasters, particularly in aviation forecasting, are accustomed to working with the surface

[1] The research reported in this paper was sponsored by the Office of Naval Research under Contract Nonr--285 (09). Reproduction in whole or in part for any purpose of the United States Government is permitted.

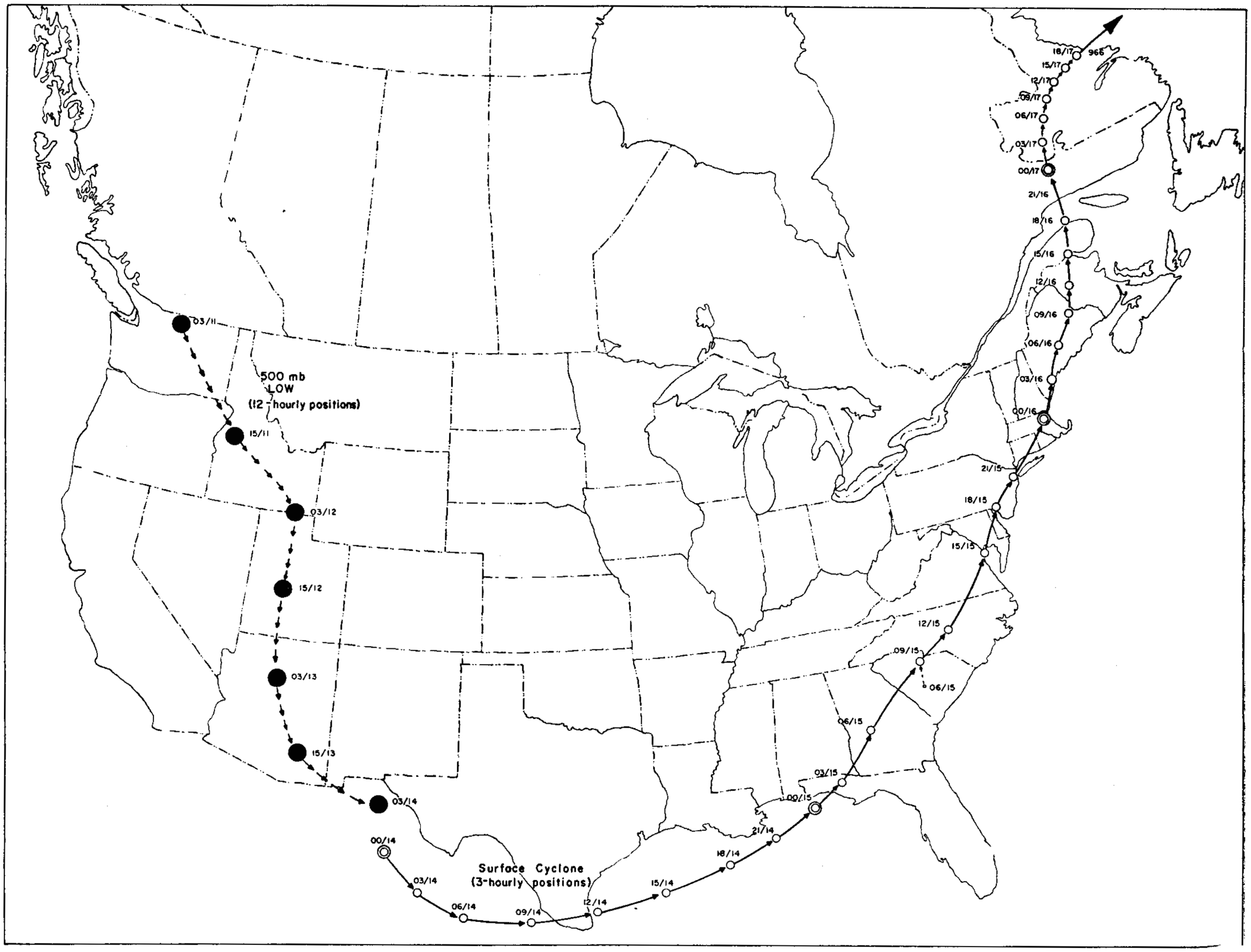

FIGURE 1.—Tracks of the 500-mb. Low (12-hourly positions) February 11–14, 1953, and the sea level cyclone (3-hourly positions) February 14–17, 1953.

synoptic, upper air, and radar scales. But a considerable part of the forecasters' attention is also devoted to what may be termed the "small synoptic scale" for which the characteristic distance in the United States is the separation between the hourly reporting airways weather stations and the characteristic time is one hour or less. When examined on this scale, the structure of fronts, the shape of the pressure field, and the distribution of rain and wind may bear little resemblance to models based on larger-scale analyses.

The case study described below was undertaken as an approach to the problem of devising a model of cyclone development in the eastern United States as seen on the small synoptic scale. However, it is not suggested that this one example is in any way a representative model of cyclogenesis. The cyclone selected was characterized by widespread heavy rain, rapid deepening, and very fast movement, all of which occurred over a region containing a suitably dense network of weather stations. It is not to be expected that other cyclones will have quite the same structure and behavior.

The original map scale used for most of the analysis was about 1:4,000,000. The airways sequence reporting stations, for which pressure and wind analyses were constructed every hour, form an irregular grid on the Atlantic seaboard with an average separation of about 50 miles (greater in the south and smaller in the north). Rainfall data, on the other hand, were obtained in 6-hourly increments for a network consisting of cooperative recording-gage stations as well as first order Weather Bureau stations.[2] The average distance between the raingage stations used was about 25 miles. This is considerably greater than is desirable for most hydrologic purposes and, with little effort, the distance could have been reduced by adding stations. However, this would have resulted in a non-uniform distribution of gage density, so that the scale

[2] Rainfall data were supplied by the National Weather Records Center, Asheville, N. C.

of the rainfall analysis would have been variable and would not correspond to that of the pressure and wind analyses.

Although some attention was given to the upper air data in this study, it is obvious that analysis on the small scale must be restricted largely to surface weather observations. Because of the relatively long time intervals and large distances between upper air reports, it is difficult, in general, to describe anything but the environment of a cyclone in three dimensions. Its internal structure is revealed only occasionally and incompletely by the synoptic upper air data.

2. THE STORM TRACK

The cyclone described below first appeared on the surface weather map in northern Mexico about 0030 GMT February 14, 1953, although it apparently originated much earlier at upper levels. The earlier phases in the life history of the storm and its behavior as it moved eastward into the Gulf of Mexico on the 14th have been described by Jones and Roe [1]. The paths of the 500-mb. Low and the surface cyclone are shown in figure 1.

A low center was found on the 500-mb. map for 0300 GMT February 11 over northern Washington prior to the appearance of the surface cyclone. In the next three days the 500-mb. Low moved southeastward (about 500 miles per day) to northern Mexico, where the surface cyclone appeared southeast of the upper Low. After the formation of the surface Low, the 500-mb. cell was absorbed in the southern end of the deepening trough. The 500-mb. Low never reappeared as a closed system but remained embedded in the southern end of the trough in the form of an area of weak pressure gradient and light wind. The surface cyclone moved eastward into the Gulf of Mexico, then turned northeastward and raced across the Atlantic coastal region on the 15th.

The cyclone center reentered the United States near Panama City, Fla. about 0330 GMT on the 15th after traversing the northwestern portion of the Gulf. Up to this time the average speed of the cyclone had been 46 knots, it had deepened about 2 mb. in 27 hours, and had been accompanied by heavy rain and very gusty winds along the Gulf coast from Louisiana to Florida.

After crossing the coast the cyclone continued its rapid progress northeastward across the coastal plain. At 0030 GMT on the 16th the center passed over Boston having travelled at an average speed of 43 knots in the preceding 24 hours. During this period the cyclone deepened 19 mb. Nine hours later the pressure reached a minimum value of 970 mb., a drop of 25 mb. in 24 hours. (In the 3 hours between 1530 and 1830 GMT on the 15th the central pressure fell 5 mb.) The deepening rate of the cyclone is shown in figure 2.

Moving now with a speed of about 25 knots the storm crossed the Gaspé Peninsula on the 16th, entered southern Quebec, and then recurved again across Labrador. As the cyclone left the Labrador coast on the 17th the central pressure again fell about 4 mb. But in the next three days

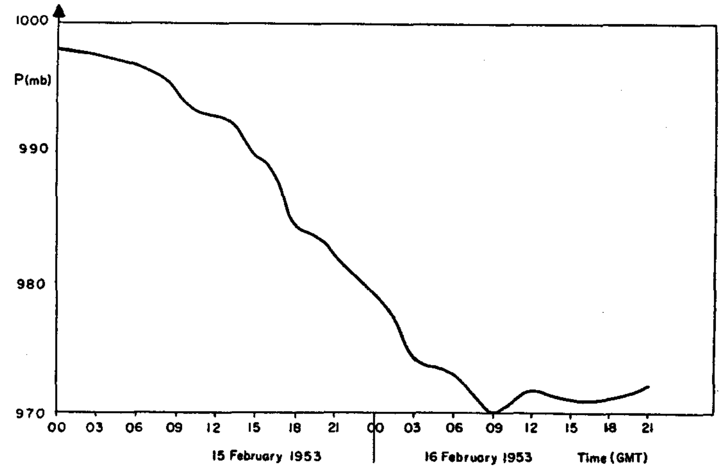

FIGURE 2.—Central pressure of the cyclone, February 15–16, 1953.

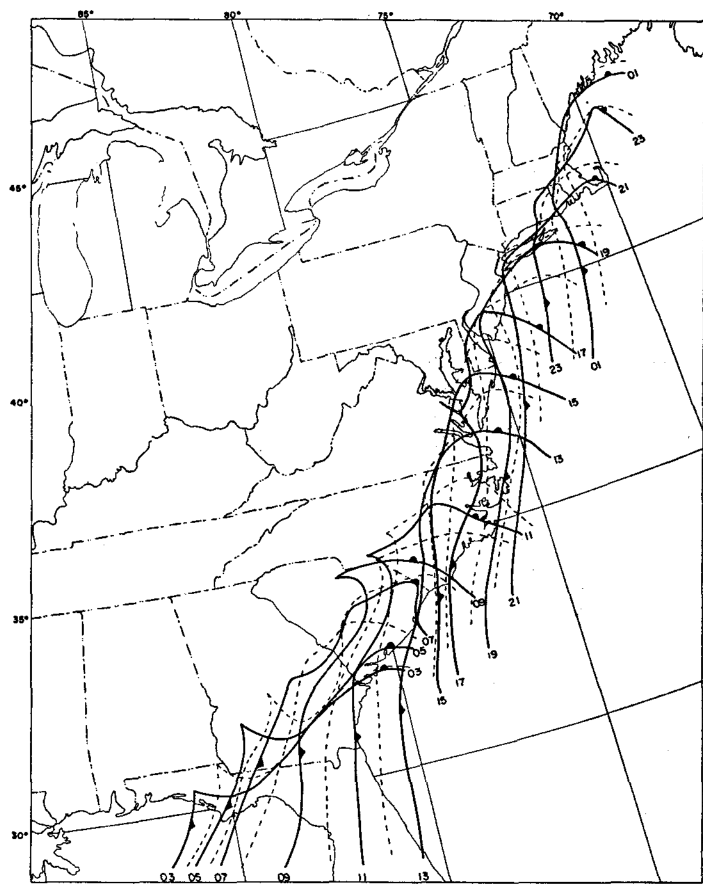

FIGURE 3.—Frontal isochrones, 0330 GMT, February 15—0230 GMT, February 16, 1953. Solid lines are positions at odd hours, dashed lines at even hours.

the cyclone slowly filled as it drifted eastward south of Greenland.

Hourly surface maps were drawn for the period 0330 GMT February 15, to 0230 GMT February 16, 1953, during which time the cyclone traversed the Atlantic seaboard from Florida to Maine. The hourly positions of the fronts (frontal isochrones) taken from the hourly surface maps are shown in figure 3. The solid curves, which are labeled

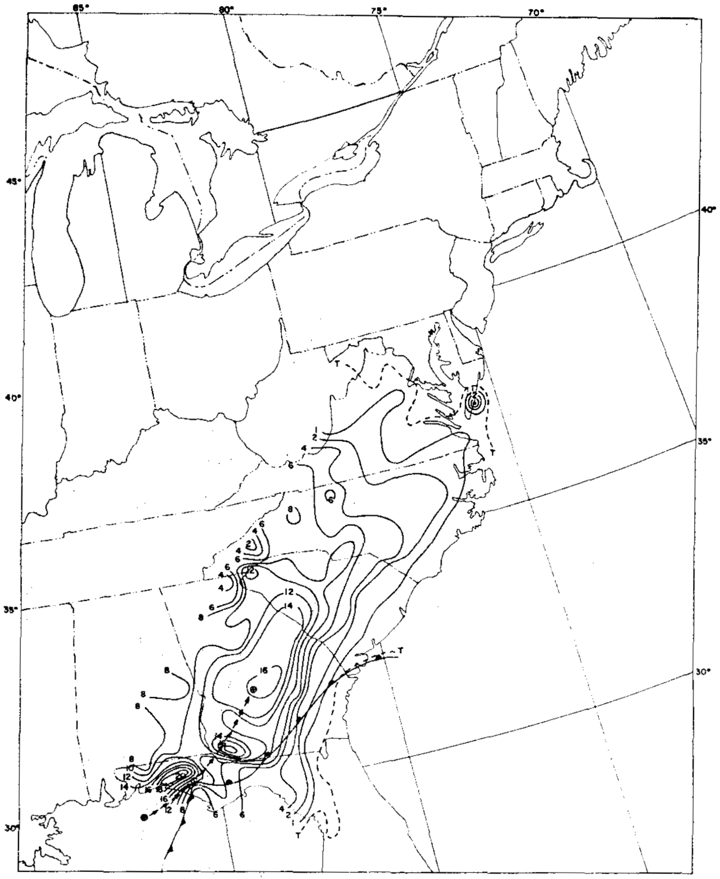

FIGURE 4.—Isohyets of 6-hourly rainfall, 0030–0630 GMT, February 15, 1953, labelled in tenths of inches. Except for the trace (T) and 0.1-inch isohyet, the interval is 0.2 inch. Arrows show the cyclone track during the 6-hour period. Frontal positions are shown for the middle of the period.

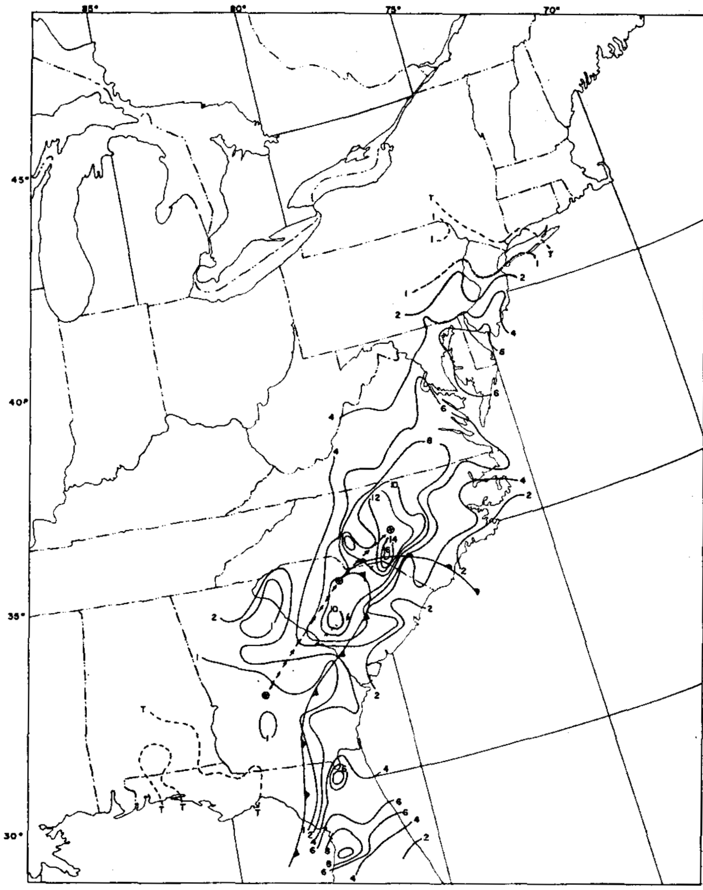

FIGURE 5.—Isohyets of 6-hourly rainfall, 0630–1230 GMT, February 15, 1953. (See legend for fig. 4.)

in Greenwich Mean Time, are drawn for odd hours, and the unlabeled dashed curves are the frontal isochrones for the even hours.

It can be seen from the frontal isochrones that, while the cyclone deepened very rapidly, the system did not occlude. On February 15 the average eastward speed of the cold front (oriented approximately north-south in figure 3) was 24 knots, while the average northward speed of the warm front (oriented approximately east-west in figure 3) was 31 knots. Thus the frontal system, as seen in the isochrones, has the appearance of a fast, flat, stable wave.

The reluctance of deepening east coastal cyclones to occlude is well known. At times the absence of occlusion may be ascribed to the fact that when the low center is on the coast the cold air west of the cold front may be advancing over land while the cold air north of the warm front is retreating over water. The smaller frictional drag at the sea surface thus permits the warm front to advance more rapidly than the cold front, and the warm sector remains open. However, in the present case it can be seen that the warm front advanced quite as rapidly over land (e. g., between 0930 and 1330 GMT) as it did over water. It will be seen below that the rapid movement of the warm front was caused by the downward transport of warm air through the frontal surface. The mixing of the potentially warmer air from above the front with the cool air below the front eradicates the "old" warm front and produces a "new" warm front well to the north. The "new" warm air south of the "new" warm front is, of course, not as warm as was the original warm sector air. This is due partly to the non-adiabatic cooling of the northward-moving warm air mass and partly to the mixing of cold air with the sinking warm mass. Since there is strong vertical wind shear through the front, the vertical mass exchange also brings strong southerly momentum to the surface ahead of the front, and this too contributes to the northward acceleration of the warm front.

3. RAINFALL

Six-hourly rainfall amounts were obtained from 275 recording raingages uniformly distributed throughout the eastern United States. Both cooperative and first order stations were used to give an average gage density of about one in 850 square miles.

The scale of the raingage network is about half as large as that of the airways network employed in the synoptic analysis. It is thus capable of revealing many

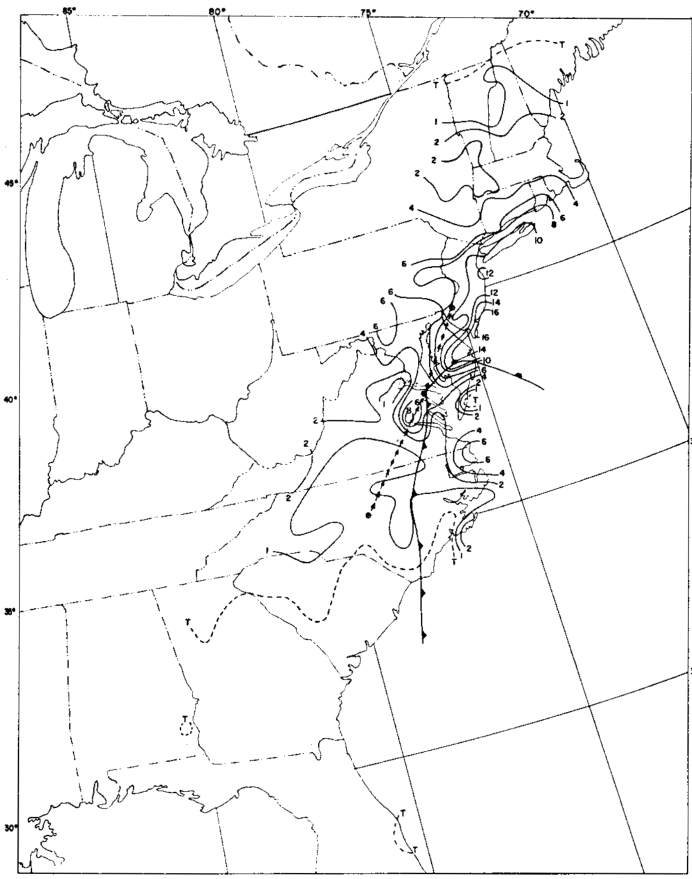

Figure 6.—Isohyets of 6-hourly rainfall, 1230–1830 GMT, February 15, 1953. (See legend for fig. 4.)

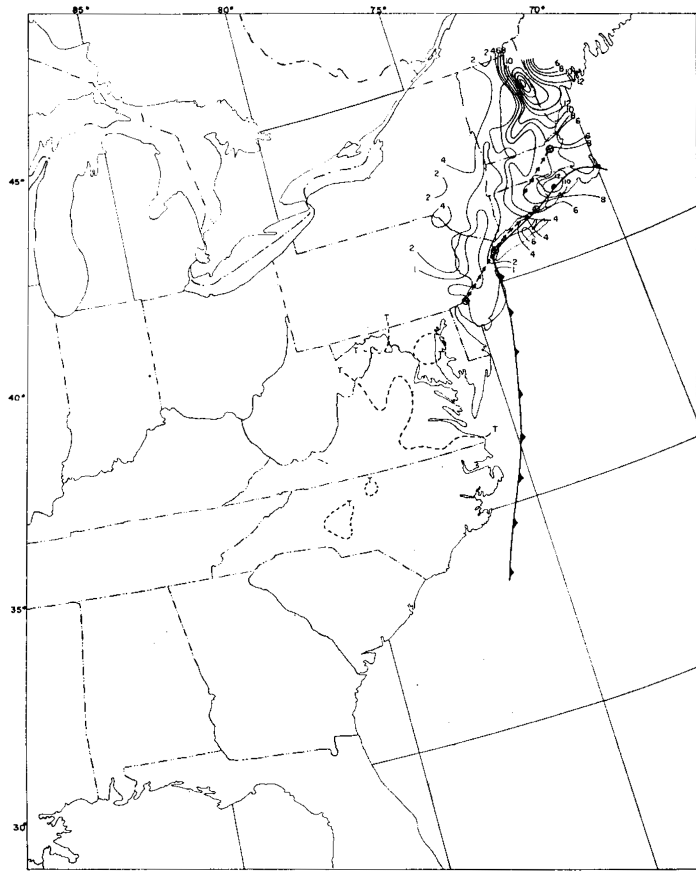

Figure 7.—Isohyets of 6-hourly rainfall, 1830 GMT, February 15–0030 GMT, February 16, 1953. (See legend for fig. 4.)

small convective rain cells which the synoptic analysis may not show. Because 6-hour totals are used and the life of a convective rain cell may be at least several hours, the effective scale of the raingage network is even smaller than the distance between gages would indicate.

The 6-hourly rainfall distributions associated with the cyclone are shown for the four periods of February 15, 1953 in figures 4–7. Isohyets are drawn for a trace (T), one tenth of an inch, two tenths, and at intervals of two tenths of an inch thereafter. Also shown on the isohyetal maps are the cyclone track during the 6-hour period and the frontal positions at the middle of the period.

The heaviest rain on February 15, both in regard to maximum point values and the area covered, occurred in the first period (fig. 4) when the cyclone was farthest south. During this period, when the cyclone was still deepening rather slowly, 6-hour rainfall amounts in excess of 2 inches fell in western Florida. The axis of maximum precipitation was oriented southwest-northeast, approximately along the cyclone track and parallel to the mid-tropospheric circulation. The rain fell mainly in the cold air north of the front, although light rain did fall also in the warm sector. It is clear from the isohyets that the rainfall had the character of cellular convection superimposed on a broad area of steady and rather uniform precipitation.

In the second period (fig. 5) moderate rain fell in the warm sector as a series of pre-frontal showers and squall lines moved eastward over the region from Florida to North Carolina. But the heaviest rainfall again occurred along the cyclone track and ahead of the low center. The center of gravity of the rainfall travelled about 50 knots toward the northeast, with about the velocity of the wind at 700 mb. Although the cellular character of the rainfall is still evident in figure 5, the strong convection which produced more than 2 inches of rain in the first period apparently diminished somewhat in the second. The maximum 6-hour rainfall observed in the latter period was 1.6 inches. It can easily be shown that the vertical velocity necessary to produce rainfall of this intensity must be at least one meter per second. Thus the characteristically heavy cyclonic precipitation in winter requires vertical motions considerably greater than the gentle upgliding associated with the large-scale circulation.

Between 1230 and 1830 GMT (fig. 6) pre-frontal showers produced patches of light precipitation in the warm air, while the heaviest rainfall (1.6 inches) again fell in the cold air ahead of the warm front.

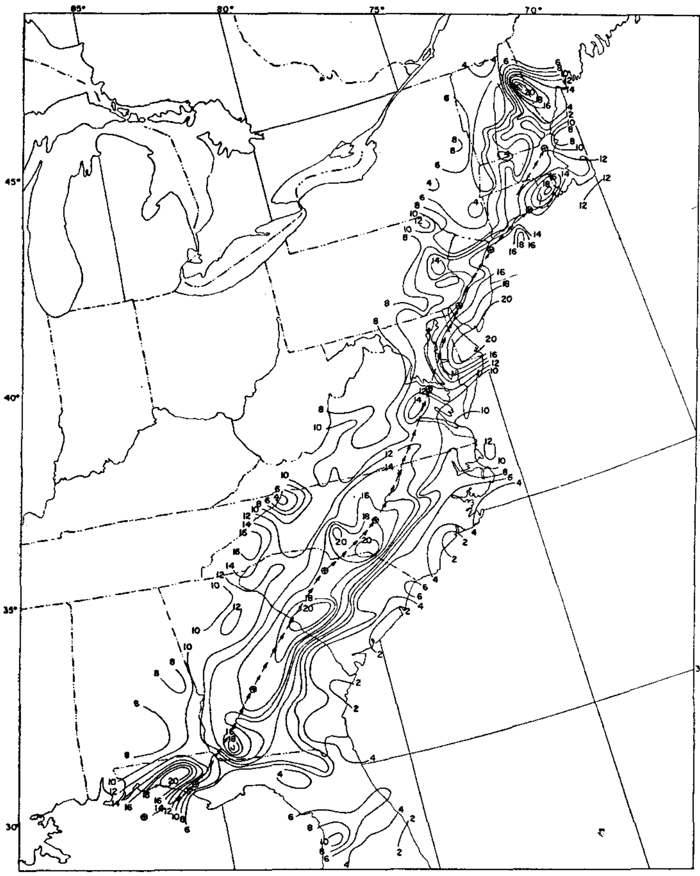

FIGURE 8.—Isohyets of 24-hourly rainfall and 24-hour cyclone track, 0030 GMT, February 15–0030 GMT, February 16, 1953.

In the last period shown (fig. 7) the precipitation was also concentrated north of the cyclone. (We have, of course, no information about the rainfall amounts over the ocean.) The heaviest rainfall (2.5 inches) was observed on Mt. Washington, N. H. That this was not entirely orographic is shown by the fact that 1.4 inches fell at Portland, Maine, at the same time. This rainfall maximum (another maximum of 1.4 inches is found over Providence, R. I.) appears to have been connected with the secondary cyclone center which appeared over Hartford at 2330 GMT and which is shown near Boston at 0030 GMT in figure 7.

The patterns of 6-hourly rainfall described above are in accord with the familiar cyclone model. With the exception of pre-frontal showers, the rain occurred mainly ahead of the cyclone center and the heaviest amounts fell approximately along the cyclone track. This is shown more clearly in figure 8 in which isohyets of the total 24-hour rainfall on February 15 are drawn, together with the 24-hour cyclone track. The cyclone track almost coincides with the axis of maximum rainfall. Exceptions are the orographic rainfall in New Hampshire and the western part of North Carolina, and the heavy rain in southern New Jersey which accompanied the passage of the cold front.

Very little rain fell along the coast south of Hatteras either in the warm sector or ahead of the warm front. However, farther north, where the low center approached closer to the coast, the coastal stations experienced heavy rain. Only quite close to the low center was the convergence strong enough to produce persistent heavy rain.

It is virtually impossible to construct a satisfactory quantitative model of cyclonic precipitation. Reiss [2] attempted to combine 43 6-hour rainfall periods from 10 east coastal winter cyclones with similar tracks (including the present storm) into a composite map. Although the resulting composite pattern resembled each of the component maps, the standard deviation in the region of maximum composite rainfall was found to be equal to the maximum itself. This result, although it is based on only a limited amount of data, is indicative of the great variability and the convective character of cyclonic rainfall in the eastern United States.

4. WIND

The mean wind (represented by the 1-minute average, the 5-minute average, or the fastest mile) is of less interest in surface wind analysis than the gust velocity. Not only is the latter more closely connected with the physical effects of the wind on people and structures, but also the gust velocities give greater insight than do mean winds into various turbulent transfer processes in the atmosphere.

An analysis of all gust velocities reported in the hourly and special airways observations on February 15, 1953, in the Atlantic coastal region led to the following conclusions regarding the low-level wind structure in the cyclone:

1. The relation between surface wind and sea level pressure distribution is different in the various sectors of the cyclone and in the different stages of the life history of the storm, and depends on the vertical shear and stability in the lower levels.

2. In the early stages of the cyclone the strongest gusts were found in the warm sector. In the cold air northeast of the low center the wind was generally light and markedly cross-isobaric.

3. The cold air under the warm frontal surface was shallow and stable with strong vertical shear through the frontal zone. The momentum of the fast-moving warm air above the front was generally shielded from the surface by the frontal stability. However, this momentum did occasionally penetrate to the surface producing isolated gusts ahead of the warm front. When this occurred, the vertical mixing caused an increase in the surface temperature ahead of the warm front and an increase in the surface wind component away from the warm front in the cold air, so that the front accelerated northward.

4. In the early stages of the storm the gustiness was not accompanied by corresponding increases in the sea level pressure gradient. However, as the storm deepened, the strong easterly winds which developed northeast of the low center were associated with roughly proportional increases in the sea level pressure gradient. This observa-

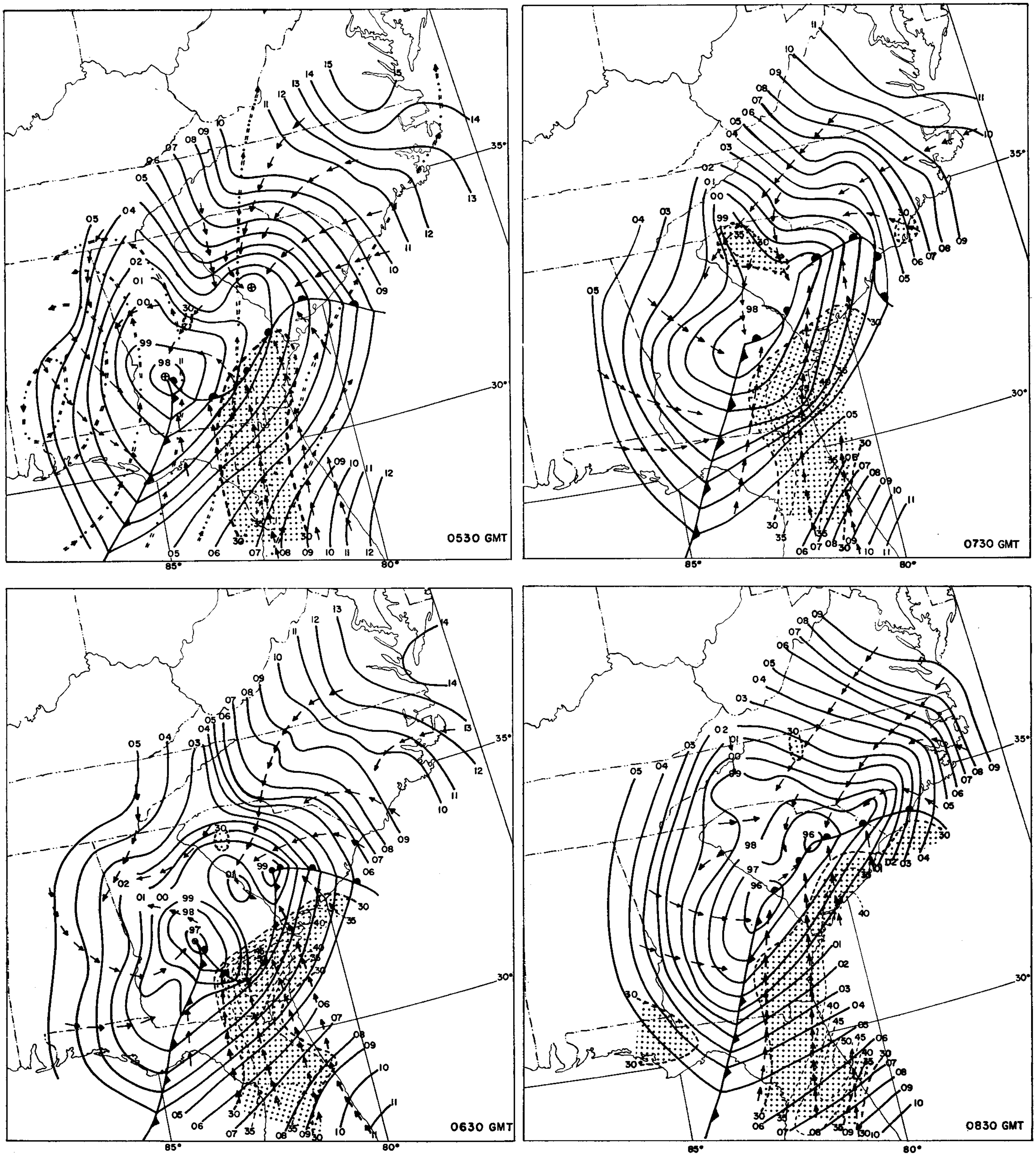

Figure 9.—Hourly surface maps, 0530–0830 GMT, February 15, 1953. Solid lines are 1-millibar isobars. Dashed lines are gust isotachs labeled in knots. The areas in which the gust velocities exceed 30 knots are stippled. Dashed arrows show the surface wind direction. The double dash-dot-dot arrows on the 0530 GMT map are 0300 GMT geostrophic streamlines (contours) at 850 mb.

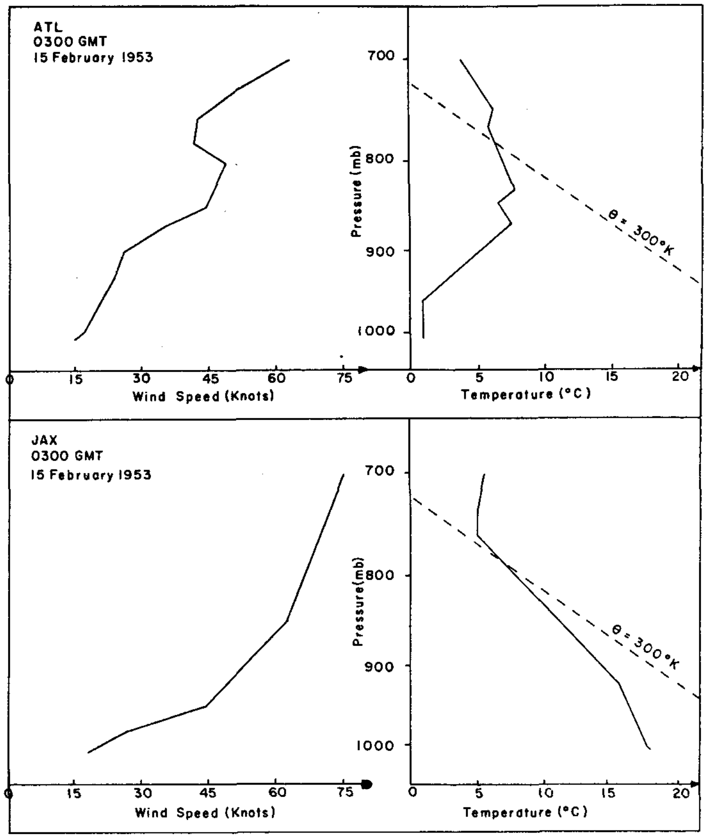

FIGURE 10.—Wind speed profiles and lapse rate curves for Atlanta (ATL) and Jacksonville (JAX), 0300 GMT, February 15, 1953.

tion suggests that the gusty winds in the cold air in the early stages of the cyclone were due to intermittent bursts of momentum downward through the stable frontal layer, whereas the strong northeasterly winds in New England in the later stages were produced by a local energy transformation associated with the increased pressure gradient rather than by vertical mass exchange.

5. The strong and gusty winds behind the cold front were generally associated with correspondingly large pressure gradients, although wind fluctuations were also observed in this region apparently without corresponding fluctuations of the sea level pressure gradient.

6. The "first gust" advanced discontinuously northward along the coast ahead of the cyclone, apparently skipping over regions of strong stability and appearing at the ground again where the stability was diminished or the shear excessive.

7. The penetration of gust momentum to the ground is inhibited when the low level wind jet (generally found about 5000 feet above the ground) is directed along the sea level pressure ascendent, since the kinetic energy of the gust is then consumed in work done against the pressure gradient force. A 40-knot gust has a kinetic energy of approximately 2 megergs gm^{-1}. It is easily shown that a particle with this kinetic energy moving along a horizontal pressure ascendent of 3 mb. per 100 km. will lose all its kinetic energy in a distance of about 60 km. The strong southerly momentum above the cold air northeast of the low center rarely penetrated to the surface in the region where the sea level gradient wind was easterly. Such gust penetration, when it did occur, was in the form of short, local bursts of strong southeasterly wind. However, in the warm sector where the gradient wind was southerly, southerly gust momentum penetrated to the surface almost continuously.

The distribution of gust velocities in the early stages of the cyclone is shown in figure 9. The four maps show the hourly pressure and gust fields for 0530 to 0830 GMT on February 15. Isobars are drawn for every millibar and gust isotachs are drawn at intervals of 5 knots for gust speeds equal to or greater than 30 knots. The surface streamlines are shown as dashed arrows. Also shown on the 0530 GMT map are the 0300 GMT geostrophic streamlines (contours) at 850 mb., represented by the double dash-dot-dot arrows.

Except for the isolated gusts in North and South Carolina which were connected with a strong pressure pulse (to be discussed later), the high gust velocities are found only in the warm sector where the 850-mb. flow parallels the sea level gradient flow. Here gusts up to 50 knots were reported in the 4-hour period shown, and later, at Wilmington, N. C., gusts to 70 knots were observed. These strong winds covered a large area of the warm sector and persisted ahead of the cold front as the cyclone moved up the coast.

Along the coast, in the cold air north of the warm front, the surface wind velocities did not exceed 15 knots. However, at 0730 GMT an isolated gust of 31 knots was reported in the cold air at Wilmington, N. C. This was the first evidence of a penetration of the front by the fast-moving warm air above the frontal surface. With the gust the temperature rose rapidly at Wilmington and the front accelerated northward. Two hours later (map not shown) a similar isolated gust struck Elizabeth City, N. C. Again the wind which had been very light from the northeast shifted to southeast, the temperature began to rise, and the front accelerated northward. These gust penetrations of the warm front continued as the cyclone moved up the coast.

The difference between the structure of the cold and warm air is shown in figure 10 in which the 0300 GMT low-level rawinsonde data are plotted for Atlanta, in the cold air, and Jacksonville, in the warm air. At Atlanta the cold air is characterized by a deep inversion (7° C. in about 5,000 feet). The wind shear in the lower part of the cold air is small, although it does increase with elevation becoming quite large across the frontal zone. However, the combination of small shear and large stability in the lower 3,000 feet over Atlanta precludes gust penetration to the surface. At Jacksonville on the other hand there is no cold shielding layer, and the wind shear, especially in the lower layers, is large so that the strong momentum above the surface can (and did) penetrate to the ground.

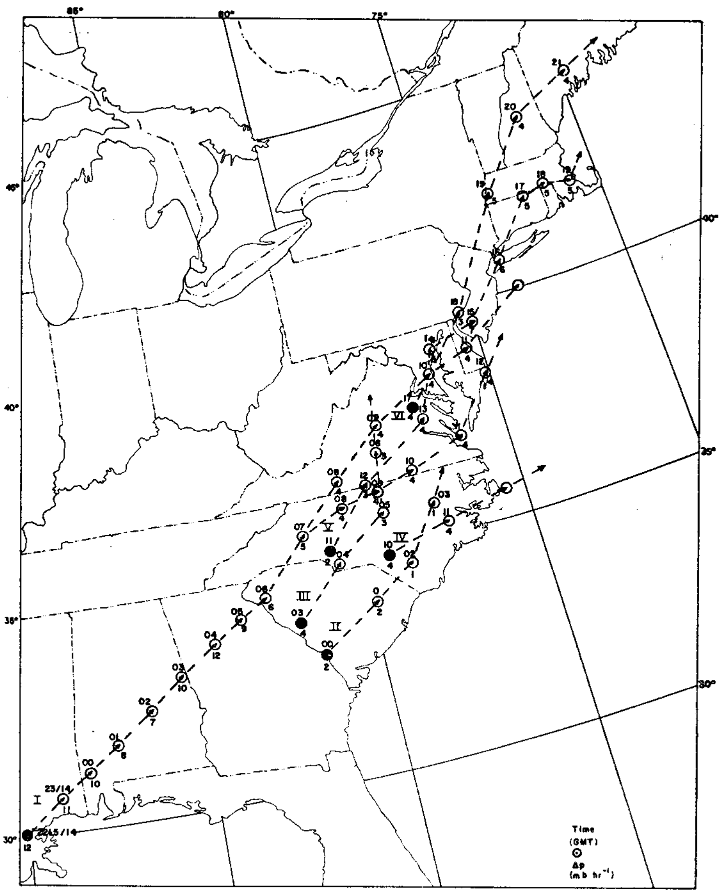

Figure 11.—Tracks of 1-hourly katallobaric centers, February 15, 1953. Solid circles show the initial positions of each of the six centers.

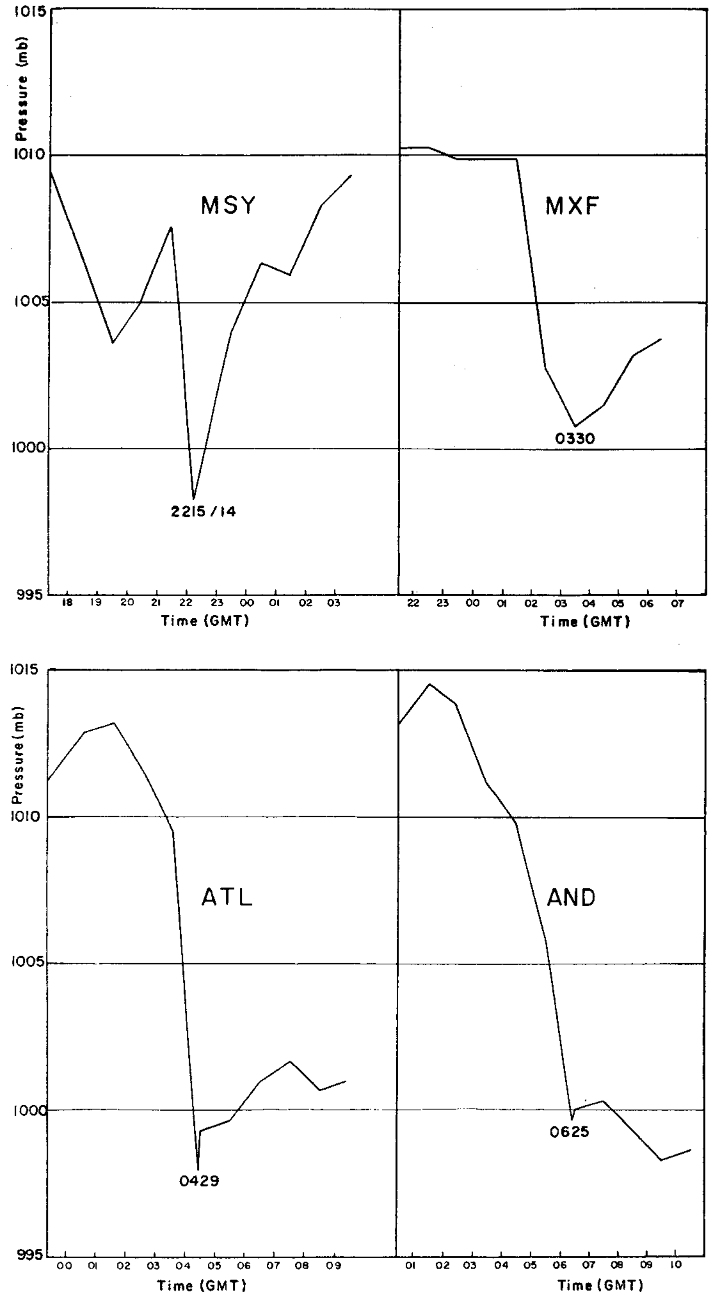

Figure 12.—Reconstructed barograms for New Orleans (MSY), Maxwell Field (MXF), Atlanta (ATL), and Anderson, S. C. (AND) showing an individual pressure pulse on February 14 and 15, 1953.

Beginning about 1730 gmt, easterly gusts in excess of 40 knots began to develop along the New England coast northeast of the cyclone. These gusts, which appeared to develop over the ocean, were associated largely with the development of a strong pressure gradient north of the warm front rather than with a vertical exchange of momentum. The absence of gusty winds north of the cyclone earlier in its history was apparently due to the relative weakness of the pressure gradient and the greater roughness of land compared with the ocean. In addition there was a noticeable decrease in the vertical stability northeast of the cyclone as it deepened which also contributed to the increased gustiness.

5. PRESSURE PULSES

Hourly isallobars drawn in conjunction with the analysis of the hourly surface maps revealed a series of pressure pulses moving rapidly across the cyclone toward the northeast. In the 24-hour period described previously six individual pulses were observed. The time, path, and 1-hourly pressure changes of each pulse are shown in figure 11. The pulses are identified with 1-hour katallobaric centers which could be followed from map to map for at least 3 hours. The average speed of the centers was 47 knots, slightly faster than the speed of the cyclone. The hourly pressure changes ranged from 1 to more than 12 mb. $hr.^{-1}$. In most cases gusty surface winds accompanied the passage of the katallobaric center and in some cases moderate rain occurred at the same time. Some of the pulses intensified and others weakened as they moved.

The katallobaric centers generally raced ahead of the cyclone producing wave-like deformations of the isobars and occasionally secondary low centers. The amoeboid fluctuations of the pressure field around the low center were apparently due to passage of the pulses across the system.

The first and most intense pulse of the group is illustrated in figure 12, showing the barograms for New Orleans (MSY), Maxwell Field (MXF), Atlanta (ATL) and Anderson, S. C. (AND) reconstructed from hourly observations and special reports of pressure jumps. The initial pressure minimum at MSY occurred with the passage of the cyclone south of the station. The pressure rose for 2 hours as the cyclone moved off then abruptly fell more than 9 mb. in 45 minutes. The increase in pressure following the minimum was almost as rapid as the fall.

The katallobaric center, which had been west of the Low raced northeastward through MXF, ATL, and AND almost without change of intensity until it was north of the cyclone. In North Carolina the pulse seemed to develop two weaker pulses which travelled toward the northeast and east-northeast respectively. At the same time the cyclone developed several secondaries which moved erratically through the Carolinas. The rapid pressure fall at ATL and AND was followed by an equally rapid rise, but only for a few minutes. Afterwards the pressure remained low. The pulse apparently had little effect on the central pressure of the Low which was deepening very slowly at this time (fig. 2). But it deformed the isobars north of the cyclone producing several elongated troughs (fig. 9).

REFERENCES

1. A. H. Jones and C. L. Roe, "The Northern Gulf Low of February 14, 1953," *Monthly Weather Review*, vol. 81, No. 2, February 1953, pp. 47–52.
2. G. Reiss, "A Composite Analysis of Cyclonic Precipitation in the Eastern United States," *Technical Paper* No. 3, Contract No. Nonr-285(09), College of Engineering, Research Div., New York University, 1955, 35 pp.